AN INVESTIGATION OF THERMAL COMFORT (THERMALLY NEUTRAL) CONDITIONS FOR THREE ACTIVITY LEVELS

by

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INTRODUCTION

Human comfort has been a subject of intense interest to mankind throughout his existance on earth. Since man first put on animal skins for protection against the cold, he has been searching for better ways to survive and live comfortably in his environment.

Within the past seventy years the investigation of human comfort has been the primary concern of many outstanding researchers both in industry and the educational institutions. The purpose of these studies has been to determine the subjective and physiological reactions and responses of subjects exposed to various environmental conditions. The aims of their investigations have been the development of comfort criteria which specify the optimum environmental conditions for human comfort at given activity levels.

In order to maintain itself in a relatively stable thermal comfort condition, it is essential that the human body maintain a close balance between heat production within the body (metabolism) and the heat loss of the body. The heat interchanges involved in this heat balance are described by the equation:

$$M = E \pm R \pm C \pm S$$

where: M = rate of metabolic heat production within the body.
E = rate of evaporative heat loss.
R = rate of radiative heat loss or gain.
C = rate of convective heat loss or gain.
S = rate of heat storage within the body, resulting in a change in body temperature.

The rate of metabolic heat production, M, is always positive. Under almost all conditions, when the skin temperature is higher than the dew point of the air, E is also positive. R and C are positive when the skin temperature is higher than that of the surrounding walls and air, but negative when it is lower. Storage, S, is positive when the body is gaining heat and its temperature is rising and negative when the rate of heat loss exceeds M and the body temperature is falling. While the body can store or lose heat for short periods of time without serious consequences, in spaces intended for prolonged occupancy thermal conditions must be such that $S = 0$ (Humphreys et al., 38). Within the thermally neutral zones for different activities the storage is equal to zero and E changes to maintain the necessary heat balance. Ideal conditions are experienced when the metabolic heat, M, is just balanced by the minimum evaporative loss plus radiation and convection.

The following descriptions of convective, radiant, and evaporative heat losses were given by McNall (55). Convective heat loss, C, is proportional to the air dry bulb temperature, air velocity, and the exposed surface area and temperature of the individual. The radiant heat loss, R, is proportional to the radiant temperature of the walls and the individuals effective radiation area and surface temperature. These two effects can be studied mathematically by heat transfer analysis. The evaporative heat lose, E, is an extremely complicated phenomenon which has been shown to be dependent upon the skin temperature

of the individual as well as the deep body temperature. Two types of evaporative heat loss have been noted. The first is insensible evaporation which occurs by water vapor diffusion through the skin with no wetting of the skin. The second is sweating accompanied by wetting of the skin.

The thermal variables considered in human comfort studies are dry bulb temperature, relative humidity, air velocity, mean radiant temperature and atmospheric pressure. Normally atmospheric pressure is understood to be near sea level as was the case for this thesis. Additional environmental factors affecting human comfort considered in this thesis were clothing and work rate.

The previous studies of human comfort have concentrated mainly on determining the responee of sedentary and slightly active subjects to dry bulb temperature of 60 to 105 F and relative humidities from 20 to 90 percent. Most of the previous investigatione of human subjects performing physical work have been limited to conditione producing heat stress or those conducted for comparison of the effect of activity on subjecte in the sedentary thermal comfort zone. It ie known that eatisfactory conditions for a pereon at work vary, depending upon the rate of work (level of activity) and the amount of clothing worn. In general it can be etated that the greater the degree of activity, the lower the temperature of the thermal environment necessary for comfort.

Correlation of the effects of the level of activity on the thermal comfort of men and women have not been fully established.

The purpose of this study was to determine the thermally neutral environment and zone for men and women with activity levels resulting in metabolic rates of approximately 600, 800, and 1,000 Btuh* for the average male subject. In addition to the votes of thermal sensation, observations were made of several physiological responses to the work rates.

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*Metabolic studies are not complete and will be the subject of a subsequent thesis by a staff member of the KSU-ASHRAE Environmental Research Laboratory.

REVIEW OF LITERATURE

The initial efforts to establish criteria for thermal comfort were initiated during the period from 1913 to 1923 when John Sheppard, at Teacher's Normal College in Chicago, was reported to have introduced the term "Comfort Zone" (Discussion by E. V. Hill to Houghton and Yaglou 36, Nevins 59). In 1923 Houghton and Yaglou published their works (36,37) which established "Lines of Equal Comfort," defined "Effective Temperature" and determined the "Comfort Zone." In these experiments the subjects walked from one room, controlled with respect to temperature and humidity, to another room that had a different temperature and humidity condition. The conditions of the second room were adjusted until the immediate reaction of the subjects gave identical comfort sensations or "Equal Warmth." These results were then plotted on a psychrometric chart and were known first as lines of equal warmth. The effective temperature was defined as "An Arbitrary Index" which combines into a single value the effect of dry bulb temperature, humidity, and air motion on the sensation of warmth or cold felt by the human body. The numerical value is that of "the temperature of still, saturated air which would induce an identical sensation" (ASHRAE Guide and Data Book 2). The comfort zone was defined as including those effective temperatures over which 50% of the people were comfortable. On this basis for clothed, sedentary subjects of both sexes, Houghton and Yaglou (36) found the zone limits to be 62 and 69F ET with a comfort line at 64F ET. The comfort

line would be at 68F dry bulb temperature for a 45% relative humidity.

Extension of the original studies were undertaken to determine the affect of air motion and clothing on comfort sensations. In 1929 a revised comfort chart resulted from the work of Yaglou and Drinker (81) on the effect of summer climate on the comfort zone. The summer zone was found to be between 64 and 79F ET. and the comfort line was 71F ET. This zone included all votes indicating that a state of comfort existed, rather than 50% or more of the votes as used in the Houghton and Yaglou (36) study.

The comfort chart that appeared in the 1961 ASHRAE Guide and Data Book was basically the same as the chart published in 1929. However, the areas indicating summer and winter comfort zones had been removed after careful analysis of the original data and laboratory experiments and in the light of field experience.

The sensation of comfort as described by Nevins (58,59) is a complex, subjective one which results from a combination of physical, physiological and psychological factors. Published research work includes fifteen or more factors which affect comfort. Rohles (65) has stated that these factors can be separated into three groups: Those factors associated with the physical environment; those factors associated with the person, or organismic factors; and those factors associated with his behavior, or reciprocative factors. Some of these factors affect comfort only slightly while others, such as air temperature, exert a

large influence on comfort. The problem of defining criteria for comfort was further complicated by the variation of an individual'e reactions from day to day, and by variatione among individuals. A precise formulation of these factors into requirements for ideal comfort would be impossible. However, it was poseible to eetablish limits which would satisfy the majority.

It is possible for each person to be hie own expert on comfort becauee, as Gagge (19) concluded, comfort is usually applied to the entire environment, including lighting, eound, smell and touch as well ae to thermal sensations and comfort is not reetricted to any part of the body. It pervades the whole.

Thermal comfort has been defined by Glickman et al., (22) as "a derived state of feeling based upon a physiological balance of the individual to hie environment wherein the thermal stimuli are of low intensity," while Nevins and Hardy (60) state that thermal comfort is baeed on the individual person's ability to maintain thermal balance with his environment by means of minor physiological adjuetments, without sweating or shivering. Some researchere have chosen to define thermal comfort by what it is not, rather than give it a positive meaning. Leopold (50) expressed it as "the absence of discomfort or annoyance due to temperature and atmospheric effect indoore." He believed that this definition avoided the confusion wrought by considering such things as etimulation and health. For the purposes of this etudy the author ohoee the definition "that condition of mind

which expresses satisfaction with the thermal environment" given by the ASHRAE standard (2) and Nevins (59). This definition provides for a positive expression by the individual and because it does not place restrictions on the physiological adjustments necessary for thermal comfort it can be readily applied to comfort criteria for persons working at activity levels greater than sedentary.

The criteria on which limits of comfort zones are based are of basic importance. Many of the zones that have been published in the past are those within which at least 50% of the subjects have been comfortable, comfortably cool or comfortably warm-presumably all the votes which have not denoted actual discomfort. Bedford (3) suggested that such a zone was too wide, "for a room can scarcely be called comfortable if nearly half the occupants are uncomfortable." Thus he recommended that only those conditions causing 70% of the subjects to vote comfortable be included in the comfort zone. In discussing the application of comfort zones to industry Leopold (50) suggested that for actual installations, the criterion should be: "What conditions are acceptable to the greatest number who do not have to pay for the maintenance of these conditions, and who are unaware that a test is being conducted?" Although each of these criteria was based upon a different view point all of them were essentually restatements of the view of Houghton (28) that the comfort zone includes those rangesof thermal conditions over which the most people are comfortable.

In 1938, Gagge, Winslow and Herrington (20) defineda zone of evaporative regulation, a zone of vasomotor regulation, and a zone of body cooling. Thermal comfort was said to exist when the body was in the zone of vasomotor regulation* and the vasomotor zone was designated the zone of thermal neutrality. Close agreement between the comfort zones and the zone of thermal neutrality was shown by Keeton et al., (47) in 1941. The definition used by this author for comfort zone or zone of thermal neutrality was defined in the ASHRAE Guide and Data (2) as the environmental conditions where "the body is able to maintain a balance between heat production and heat loss without significant changes in any of the readily measurable indices of thermal comfort."

The thermally neutral temperature was defined by this author as the dry bulb temperature desired most frequently by the subjects for thermal comfort within a zone of thermal neutrality. This definition was necessary because dry bulb temperature was used; therefore, the comfort line associated with the effective temperature scale was not appropriate.

Thermal sensation (or comfort) vote scales have been widely used by investigators to determine a subject's response to a given environment. A typical scale began with "comfortable" then proceeded through the steps "slightly uncomfortable," "uncomfortable," "very uncomfortable" and "intolerable." Another scale was

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*Zone of vasomotor regulation: heat production equal to the net heat loss by convection, radiation and evaporation with no change in stored energy and without sweating or shivering.

in degrees of pleasantness: "Pleasant," "Indifferent," "Slightly Unpleasant" and "Unpleasant." Two scales which provided an arbitrary numerical scale for gathering and correlating subjective thermal sensations of comfort felt by human beings and which are presently widely used, were introduced by Houghton and Yaglou (36) and by Thomas Bedford (Hickish 27). The former's scale was (1) "cold," (2) "cool," (3) "slightly cool," (4) "comfortable," (5) "slightly warm," (6) "warm," and (7) "hot," while the latter's was (+3) "much too warm," (+2) "too warm," (+1) "comfortably warm," (0) "comfortable," (-1) "comfortably cool," (-2) "too cool," (-3) "much too cool." These verbal scales, as a first estimate, have proved useful and given many meaningful results and through their use a comfort zone has been derived which has been closely related to thermal sensation. However, it is quite easy to find situations where the sensations described by these scales are inadequate. An example was given by Gagge (19) where "everyone has experienced conditions which may be described by saying 'pleasantly warm' in winter, or 'pleasantly cool' in summer." It would be difficult for anyone to fit these contrasting sensations into the conventional scales of comfort.

Houghten et al., (33), Nevins (59) and many other researchers found dry bulb temperature, relative humidity, air motion and mean radiant temperature, or the temperature of the surroundings to have the greatest influence on human comfort. Recent works by Fahnestock et al., (15) and Nevins et al., (61) have indicated the need of adding clothing and rate of work to this list. These

factors define the thermal environment and affect the heat exchange of people. Previous investigations of the effect of these factors on the comfort zone of people performing physical work have been quite limited.

The first studies on the effect of activity were conducted in the research laboratory of the American Society of Heating and Ventilating Engineers in 1930 in Pittsburg, Pennsylvania by Houghton et al., (35). A series of three work tests were performed by four normal male subjects clothed in business suits made of mixed cotton and wool at effective temperatures of 28 to 91F and relative humidities of 20 to 95%. The purpose of the study was to establish the relation of the metabolic rate and the rate of sensible and latent heat elimination from the bodies of working men to the temperature and humidity of the surrounding atmosphere. The three work rates were 2289, 4578 and 9157 kgm per hour.* Energy production within and total heat loss from the body were shown to have similar characteristics as that of men seated at rest, but were of greater magnitude, the points of change from thermal equilibrium occurring at lower temperatures for men working. The excessive heat produced in the body due to work was shown to be dissipated largely by increased evaporation. In a later study Houghton et al., (34) presented a comfort zone for men normally clothed and working at 33,075 ft. lb/hr, at 46 to 64F effective temperature with a comfort line of 53 deg.

*1 Kg. M. = 7.233 Ft. lb
1 Cal/M^2 = 0.36867 Btu/ft^2

Graphs of predicted evaporative, sensible and total heat loss as a function of effective temperature and metabolic rate were also given. The comfort zone presented represented comfort votes from slightly cool to slightly warm. The applications of these early works were to the air conditioning and cooling of theaters, auditoriums, dance halls and other places of assemblage where people were active, and in industrial plants where the highest efficiency and comfort of workers were desirable.

In 1944, Robinson et al., (64) investigated the effect of hot environments on walking on a treadmill versus resting for subjects both nude and clothed in Army jungle uniforms. The tests were 2 to 6 hours in length in dry bulb temperatures of 73 to 122F. They found that men walking in shorts maintained thermal equilibrium from the second through the sixth hour of exposure at 93F with 91% relative humidity and a 122F with 21% humidity when their metabolic rates were 188 Cal/M^2 per hour. A metabolic rate of 130 Cal/M^2 per hour gave similiar temperatures and relative humidities. The clothed men maintained thermal equilibrium at the respective metabolic rates only in environments distinctly less severe than those listed above for men in shorts. Similar studies were performed on exercising men exposed to cold in order to establish limitations on exposure time as a function of temperature and clothing.

Activity studies were not limited to the laboratory. In 1946, comfort reactions of 275 workers during occupancy of air conditioned offices were evaluated (Rowley 66). The desired dry

bulb temperature for comfort was 74F and variations of relative humidity between 35 and 60% caused no change in the feeling of comfort. The lack of humidity effect on the feeling of warmth was ascribed partly to inherent limitations of the effective temperature index (noted by Yaglou (79)) and partly to the many factors which enter into an individual's feeling of warmth.

Recent work by Fahnestock et al., (15) of clothed men found that men exposed to 75 F dry bulb temperature and 45% relative humidity expressed thermal comfort although the average total heat productions were 599.5 Btu/hr. The heat equivalents of the average sweat losses were 40.3, 53.5, 59.0 and 61.5% of the average total heat production for the respective work rates of 600, 1400, 2000, and 2400 ft lb/min. A later report by Fahnestock, which will soon be published, that investigated the same parameters at a 95F dry bulb temperature and 50% relative humidity, emphasized the dramatic effect dry bulb temperature has on the subjective and physiological responses of a working subject.

The high evaporative weight loss experienced by the exercising men because of increased metabolism is similar to the effect Miura (56), Brebner (4), Jennings and Givoni (46), Winslow et al., (75) and other described for the resting subject when exposed to temperatures above 76F. In both cases evaporation became the primary method of body heat removal.

Two important factors which were overlooked by researchers until recently were the effect of clothing and differences in

sex on the comfort zones for various activities.

There have been a large number of publications dealing with the reactions of men to activity and changes in the environment, but very few studies with women. Why there has been such a neglect of half our population is not clear.

Hardy and DuBois (24) observed that upon comparing the results for nude resting males and females that the heat loss for females in the cold zone was about 10% lower than that of the males and that females had a lower skin temperature. (The lower skin temperature was also observed by Hardy and Milhorat (25) and discussed by Hardy and Yaglou (79)). Also in temperatures from 86 to 90F under standard conditions the metabolism of most of the women was 14-20% lower than for men. Investigation of basal metabolism by Hardy and Milhorat (25) revealed similar differences. It was also found by Hardy and DuBois (24) that females did not need to sweat as soon or as much as males in hot environments because they had a lower production of heat in their bodies, and that the comfort zone, in which the heat loss and heat production were equal, extended over a range of about 6°C for women instead of 2-3°C for men. Inouye et al., (44) observed that rates of heat loss by evaporation were less for women than for the men exposed to identical environments but that the thermal sensations were the same. In another study Inouye et al., (43) found that within the experimental ranges studied, the behavior of both sexes was quite similar and indicated that the presence of men and women in the same space did not require

alterations in accepted specifications for air conditioning.

Early data taken by Houghten et al., (29) indicated that there was no material difference in the degree of cooling desired by women over that found for men but that clothing did have a material effect upon the desired temperature for comfort. "When men and women wore similar clothes they were comfortable at almost the same environmental temperature, despite the great difference in their metabolic rates," Yaglou and Messer (82) concluded; "the difference in comfort standards between men and women were largely due to differences in dress and could be reconciled by adjustments of clothing, according to susceptability to cold or heat." Chester (10) similarly attributed the differences in male and female comfort conditions to clothing. Werden et al., (72) investigated the effect of varying fiber content in clothing and found that none of the normal indicies of thermal comfort (comfort vote, weight loss, rectal and skin temperatures) showed a significant difference due to variation in clothing fibers. Thus only variations in clothing weight and physiological differences in sexes appear to cause the observed differences seen in male and female comfort votes. Hickish (27) concluded that although men did wear more clothing than women that "if there was personal freedom of choice of clothing, men and women . . . in light occupations did not require different thermal conditions."

Activity must be considered in the development of a complete comfort chart. Winslow (74) has suggested that the comfort zone

may vary over a range of 25F, and recognized the need for further research. As summarized by Fahnestock and Werden (16) most of the existing data pertaining to the levels of environmental factors which affect human comfort are limited to sedentary or slightly active healthy young men and women. Similar data are urgently needed for people working at various rates. The research summarized here has pointed out those areas which have been investigated and which will be of greatest importance in connection with future studies of environments for people doing physical work.

MATERIALS AND METHODS

Experimental Facilities

The experimental program was carried out in the KSU-ASHRAE Environmental Test Chamber which was placed in operation at Kansas State University in November, 1963. This facility was originally located at the ASHRAE Cleveland Laboratory (See Jennings and Givoni (46) for a description of the room at that facility).

A floor plan of the chamber and adjoining rooms is shown in Fig. 1. The environmental chamber is 12 ft. wide, 24 ft. long and has a ceiling height adjustable from 8 ft. to 11 ft. All interior surfaces are made of aluminum panels. The surface temperatures of each panel are controlled by circulating heated or chilled liquid through copper tubes attached to the back of each panel. The liquid circuits and panel sizes were chosen to provide maximum flexibility in selecting combinations of panels to simulate glass and wall areas, or as was true for the tests described for this study, the wall temperatures were adjusted to produce surface temperatures essentially equal to the dry bulb temperature being maintained in the chamber. Surface temperatures of 40 to 150F could be obtained. Conditioned air enters through perforated inlet strips located between the ceiling panels and leaves through a continuous slot at the floor around the perimeter of the room. Details of construction and basic piping circuits can be found in Tasker et al., (69).

The following equipment was placed in the test chamber for

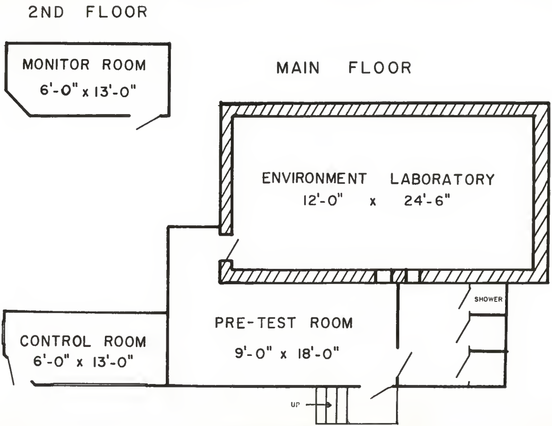

Fig. 1. Floor plan of KSU-ASHRAE environmental facilities.

this study: four 4ft high tables, ten drinking cupe, an enunciator, a stand-walk sign and ten 9 inch "two stepe."

The air-conditioning system can control the dry bulb temperature at any desired level from 40 to 150F. The relative humidity can be maintained at any level from 10 to 95% throughout this dry bulb temperature range. The system coneists of a capillary washer, a sorption dehumidifier, separate heating and cooling coils, fans and ducting. Provisions for circulating up to 50 air changes per hour were made.

A chilled liquid (water) supply tank wae maintained at a given temperature with a 15 hp refrigeration compressor and a hot liquid supply tank was maintained with steam supplied by the Kansas State University's boilers. Ueing a system of mixing valves, liquid with the desired temperature can be circulated through the panels in the test chamber. Four independent circuits were available: floor, ceiling and two in the walls.

The entire eystem was remotely and automatically controlled from the control room adjacent to the pre-test room (Fig. 2). A combination of electronic and pneumatic control equipment was used. Two graphic control panele were provided, one for the air circuit and one for the liquid circuits. Lights indicated thoee parts of the system which were in operation. Air or liquid temperaturee at varioue indicated locations in the eystem could be monitered.

An indicating potentiometer and a multipoint recorder were provided to measure wall surface temperatures and air temperatures.

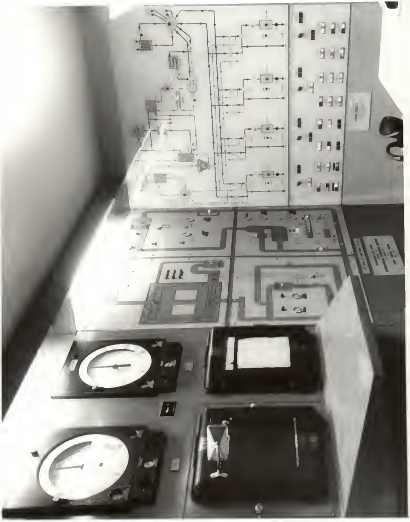

Fig. 2. Control room for KSU-ASHRAE environmental facilities.

A physiological monitoring room was located above the control room. Instrumentation for measuring skin temperature, rectal temperature and heart rate was available. Operant conditioning and programming equipment was also located in this room.

The entire facility was located in the Institute for Environmental Research building funded by Kansas State University with a matching grant from the Health Research Facilities Branch of the National Institute of Health. This building was constructed to house this apparatus and to provide a focal point for environmental research (Nevins et al., 61).

Test Subjects

The test subjects were healthy college students, including 210 males and 210 females, with a mean age of 20 and 19 years respectively, ranging in age from 17 to 25. All subjects were volunteers from the student population of Kansas State University who received $5.00 for participation. No subject was allowed to participate more than once at a single activity level. During each test, the subjects were exposed for 3 hours in groups of 10, 5 men and 5 women, to only one dry and wet bulb combination. The physical measurements of the average male and female subject participating in the study are shown in Table 1. DuBois' (16) formula for body surface area for a nude body was used because previous measurements of surface area for clothed subjects have found that the clothed surface area of a standing man were almost the same as that found for nude human subjects.

Table 1. Physical measurements of the average male and average female subject participating in the activity study.

Subject	Age (Yrs.)	Height (in.)	Weight (lb)	*Body Surface Area (Ft^2)
Average male	20	69.8	163.4	20.63
Average female	19	64.8	130.4	17.75

*DuBois (16) formula for body surface area.

Clothing

Nude subjects were used in many of the previous investigations of human comfort. From the physiological and statistical point of view, the use of nude subjects has as an advantage the elimination of clothing as an experimental variable. However, the ultimate application of comfort study work is to men and women working in a temperate climate where clothing is worn both winter and summer. Therefore, although clothing presents an additional variable which must be considered, clothed subjects were used in this study. To minimize variation due to clothing all subjects were clothed in cotton twill shirts and trousers (similiar to clothing worn by service station attendants) with the shirts worn outside the trousers. Male subjects wore cotton undershorts or jockey shorts but no undershirts or T-shirts. Brassieres and underpants were worn by the women. All subjects wore woolen socks without shoes. It was felt that this type and weight of clothing was typical of that normally worn by male

persons working at or near the activity levels investigated. The same type of clothing was worn by subjects in the sedentary comfort study by Nevins et al., (61). Similar clothing was used in activity studies by Fahnestock et al., (15) and Inouye et al., (43).

The insulating value of the clothing was measured by the Army Research Institute of Environmental Medicine and by the Institute for Environmental Research, Kansas State University and was found to be about 0.52 Clo. The author believes that the clothing normally worn by men and women indoors while working within the range of activity levels investigated is approximately 0.5 Clo. The Clo. values given by Yaglou (80) were slightly higher; however, it is believed that the present day clothing worn by males and females is generally of lighter total weight and lower insulating value than the clothing worn in the 1930's and 1940's. Figure 3 shows a typical male and female subject in the standardized clothing as developed by Nevins et al., (61).

Experimental Design

Three activity levels representing metabolic rates of approximately 600 (low activity level), 800 (medium activity level), and 1,000 (high activity level) Btu/hour for average male subjects were selected. These rates represent step increases of the sedentary male metabolic rate of approximately 400 Btu/hour and (as described in the ASHRAE Guide and Data Book, 2) were felt to be representative of distinct daily activities that a man or

Fig. 3. Male and female subjects in standardized clothing consisting of cotton twill shirt, trousers and sweat socks.

woman would experience in indoor environments. Examples of practical activities or occupations resulting in similar metabolic rates are shown in Table 2 (ASHRAE Guide, 2; Chaney, 9; and White, 73).

Table 2. Typical examples of activities and occupations for the metabolic rates investigated.

Metabolic Rate* (Btu/Hr)	Activities and Occupations
600	Sitting, moderate arm and leg movements, driving car in traffic, housemaid, typewriting rapidly, ironing, and washing floors.
800	Sitting, heavy arm and leg movements, standing, moderate work at machine or bench, shoemaker, and walking (3 mph).
1000	Walking about, with moderate lifting or pushing, carpenter, metalworker and industrial painter.

*Approximate value for the average male.

The basic experimental design consisted of nine temperature-humidity combinations (shown in Table 3) for each activity level. Using previous data from the ASHRAE Guide and Data Book (2) and the activity studies by Houghten et al., (34,35), Fahnestock and Werden (16) and Fahnestock et al., (15), design test combinations were chosen that included the expected temperature limits for each thermally neutral zone. The tests were randomized as to

Table 3. The experimental design of temperature-humidity combinations for the three activity levels.

Low Activity Level

Relative Humidity	Dry Bulb Temperature (F)		
	66	72	78
25	E	E	A
45	A	A	E
65	A	E	A

Medium Activity Level

Relative Humidity	Dry Bulb Temperature (F)		
	60	66	72
25	A	E	A
45	E	A	E
65	A	E	E

High Activity Level

Relative Humidity	Dry Bulb Temperature (F)		
	54	60	66
25	A	A	E
45	E	A	E
65	A	E	A

A = Afternoon Test
E = Evening Test

time of day (afternoon or evening). Mornings were avoided since previous work by Jennings and Givoni (46) and Nevins et al., (61) indicated the results of morning tests were significantly different from afternoon and evening tests. This was probably due to the effect of diurnal metabolic cycles. Iampietro et al., (42) found that moderate activity during the day did not remove or change the effect of the diurnal cycle. In February, 1966, several preliminary tests were conducted to verify the predicted thermally neutral temperatures and standardize test techniques.

For each activity level, the central temperature of the three was selected as that of the predicted "thermally neutral," or "thermal comfort" temperature. The 6F interval was chosen since it represented approximately a unit thermal sensation vote difference by subjects in previous tests by Nevins et al., (61). The three relative humidities (25,45,65%) were chosen because they include the practical extremes for normal environmental control as described by Houghton et al., (34), Houghton and Gutberlet (30), Bedford (3), Carrier (8), Nevins and Hardy (60) and others. The same relative humidities were used for each activity level, and the humidity effect on thermal sensation was predicted to be small or negligible. Subjects were randomly assigned to the 9 possible treatment combinations, resulting in a completely randomized design for the activity.

The statistical model was:

$$^{*}Y_{ij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \epsilon_{ij};\ i = 1 \ldots a,$$
$$j = 1 \ldots b, \quad {}_{ij} = N(0,\sigma)$$

where:
Y = observed mean vote.
μ = overall mean vote.
α_i = effect of the i^{th} level of temperature.
β_j = effect of the j^{th} level of humidity.
$(\alpha\beta)_{ij}$ = interaction effect of the i^{th} level of temperature and the j^{th} level of humidity.
ϵ_{ij} = random error of the ij^{th} observed mean.

The analysis of variance shown in Fig. D-5, in the appendix, from Cochran and Cox (12) and the F-test were used to analyse the means of the thermal sensation votes. A multiple regression analysis using a computer program for the 1410 IBM computer was used to fit a surface through the means of the thermal sensation votes in the temperature-humidity plane. The multiple regression analysis allowed the author to determine the observed mean vote as a function of the linear effect of temperature and relative humidity on mean comfort votes. The multiple regression model was

$$Y_i = \mu + \beta_1 x_{1i} + \beta_2 x_{2i} + \beta_3 x_{3i} + \beta_4 x_{4i} + \beta_5 x_{5i} + \epsilon_i$$

where:
Y_i = observed mean vote for i^{th} observation.
μ = overall mean vote.
β_1 = partial regression coefficient associated with x_1.
x_1 = level of temperature for i^{th} observed value.
β_2 = partial regression coefficient associated with x_2.
x_2 = level of relative humidity for the j^{th} observed value.
β_3 = partial regression coefficient associated with x_3.
$x_3 = x_1 x_2$
β_4 = partial regression coefficient associated with x_4.

*From Snedecor (68).

$x_4 = x_1^2$

β_5 = partial regression coefficient associated with x_5.

$x_5 = x_2^2$

ε = random variable associated with sampling variation.

The F and t tests provided evidence for selecting a form for the regression function.

For each activity level, a stand-walk cycle using a modified step test was developed by varying the stand period and using a 5 minute walk over two 9-inch wooden steps (shown in Fig. 4). The walk consisted of ascending and descending two 9-inch steps at the rate of one step per second. Preliminary analysis of the walk, as measured by oxygen consumption, in the Institute for Environmental Research has indicated that the energy cost to the average male was approximately 1600 Btuh. This metabolic rate is equivalent to the average man walking fast (4.8 mph), climbing and descending stairs (2 flights/min), doing deep knee-bend exercise (33/min) or performing the Master two-step test (Ford and Hellerstein, 18). The stand period was found to have an energy cost of approximately 430 Btuh for the average male. The equipment and procedure used in the Master two-step test (Master, 51) are similar to those used in this step test.

The resulting cycles were stand 25 minutes - walk 5 minutes for the low activity level; stand 10 minutes - walk 5 minutes for the medium activity level; stand 5 minutes - walk 5 minutes for the high activity level.

Figure 5 is a facsimile of the thermal sensation ballot used

Fig. 4. Male subject during 5 minute walk period on two 9" steps.

by the subjects. It shows the thermal sensation scale used. It is similar to the thermal comfort scale developed by Houghton and Yaglou (30) with "comfortable" replaced by "neutral" for a No. 4 vote as suggested by Gagge and Hardy of the John B. Pierce Laboratory, New Haven, Connecticut. Statistical analysis using sedentary test data was used to verify the validity of the thermal sensation scale and to justify its use. Appendix A details this justification. This scale was felt to be more scientifically descriptive and adaptive to non-uniform thermal effects planned for the future. (In future studies, it may be possible for a subject to feel thermally neutral, yet uncomfortable due to the non-uniformity. In these cases, thermal neutrality and comfort will be evaluated separately.)

Subject Name____________________ No.________

Circle the number that describes how you feel.

1. cold
2. cool
3. slightly cool
4. neutral
5. slightly warm
6. warm
7. hot

Fig. 5. Thermal Sensation Ballot.

Physical Measures

Throughout the tests efforts were made to maintain wall temperature equal to air temperature. The wall-surface temperatures were determined by means of thermocouples on the surfaces, which were connected to the electronic indicating and recording potentiometers on the control panel in the control room. The globe temperature was obtained by thermocouples centered in the globe and connected to the potentiometer. The relative humidity was measured by an aspirated psychrometer placed directly in the test chamber and shielded from radiant effects. Dry- and wet-bulb temperatures were taken in the room, using the aspirated psychrometer, with mercury-in-glass thermometers. Wet- and dry-bulb resistance thermometers located in the same air stream were connected to electronic controller-recorders on the main control panel where both temperatures were indicated and recorded. All temperatures were taken at one hour intervals.

Previous analyses of air motion within the room and in the vicinity of the subjects showed air movement as measured by a hot wire anemometer was between 20 and 30 Fpm for all tests. A sample of the recorded air velocities is shown in Fig. D-1, in Appendix D.

Procedure

In all cases the test exposure was three hours at the same activity level and thermal conditions. The afternoon tests were

conducted from 1:30 pm to 4:30 pm and the evening tests from 6:30 pm to 9:30 pm. All tests reported in this study were conducted during February, March, May and September, 1966.

The subjects reported for the tests approximately 1 hour before the scheduled time for the tests to begin and dressed in the special clothing. They then entered the pre-test room. The subjects' age, height, weight, pulse rate, oral temperature and a summary of their recent physical activity were taken by a registered nurse and recorded on record sheets. Samples of the two record sheets are shown in Fig. D-2 and D-3 in Appendix D. No subject was permitted to participate whose oral temperature was above 99F. The subjects stayed in the pre-test room for 30 minutes; during this time they were indoctrinated regarding the purpose and conduct of the study and the method of voting using the thermal sensation ballot. Appendix B contains the indoctrination information. The subjects were not told the room's temperature or relative humidity until the test was completed and they had left the test room.

It should be noted that even though 10 subjects participated in each test 12 were scheduled to permit a male and female substitute in the event a subject had an elevated temperature or failed to report for the test. Extra subjects were then used as assistants for the experiments.

Upon entering the test chamber, subjects were assigned positions at the four 4ft high tables located in the center of the room (Fig. 6) and drinking cups for the duration of the test.

Fig. 6. Male subjects during stand period of the stand-walk cycle.

They were told to go to the nearest 9" step for the walk period and to use it for the remainder of the tests. The steps were uniformly distributed around the perimeter of the room.

The activity cycle began with the stand period followed by the walk period. This cycle continued for three hours. Subjects were allowed to read, study, play cards, and quietly converse while standing. An enunciator (1 "click" per second) and a stand-walk sign (see Fig. 4) were used to pace the walk and to indicate the stand-walk sequence. The pulse rate of each subject was taken just after he completed a walk period, and again just before he started his next walk period during the first hour of the test. A sample record sheet of the pulse rates is shown in Fig. D-4 of Appendix D. This procedure was repeated during the third hour of the test. These data were compared to determine the physiological stress imposed on the subject. The subjects were allowed to drink as much water as desired with each subject's consumption being recorded by the nurse. No food was consumed by the subjects during the tests. Subjects did not leave the test chamber once they had entered it until the test was completed.

Approximately one hour after entering the test chamber, the subjects reported their impression of thermal sensation by circling the number on the ballot (Fig. 5) that described their thermal sensation. After this vote was taken, the ballots were collected and the votes were tallied and recorded on the record sheet shown in Fig. D-2 of Appendix D. One half hour later, the second vote was taken and recorded. This was repeated after each

of the three subsequent half hour periods until five votes had been taken. The voting times were approximately 1.0, 1.5, 2.0, 2.5, 3.0 hours after entering the chamber. These voting times were designated as the A, B, C, D and E votes respectively.

All votes were taken during the stand period. The exact time of voting was determined from a pilot study outlined in Appendix C. This was necessary due to the cyclic nature of the activity during the tests, which caused a variation in the thermal sensation with time. For the three activity levels the votes were taken 12 minutes after walking for the low activity level, 4 minutes after walking for the medium activity level and 2 minutes after walking for the high activity level.

At the end of the third hour, pulse rates were taken for all subjects, and they re-entered the pre-test room where final weights were taken. The amount of water remaining in the cups was weighed and recorded on the record sheet shown in Fig. D-3 of Appendix D. The subjects were then paid and dismissed.

RESULTS

Statistical analyses using the analysis of variance technique and the F test were made using the means of the thermally neutral votes shown in Tables 4 and 5 for males and females respectively at the three activity levels. The F values for the five voting times (A,B,C,D and E) of both sexes for each activity level were computed to determine the effect of dry bulb temperature and relative humidity on subject voting for each voting time. Figures D-6 (for males) and D-7 (for females) in Appendix D contain the F values; the significant factors for each of the voting times were indicated. A probability of 0.05 (5%) was used for the tests of significance.* Dry bulb temperature was found significant for almost all the voting times in each activity level. Relative humidity was nonsignificant except for the female low and high activity levels; however, an overwhelming effect of temperature in the low activity level for females was also observed. It was not possible to replicate each of the tests in the low and medium activity levels; therefore, no measurement of the interaction effect of temperature and humidity could be made at these activity levels. A complete replication

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*Non-significance meant that the hypothesis being tested could not be rejected and that the difference could be attributed to random, uncontrolled variation. Significance meant the hypothesis was rejected and that something has happened in the experiment that would be expected to happen by chance less than one in twenty trials. Therefore, some difference in mean votes does exist that cannot be accounted for by random, uncontrolled variation. Thus, the difference observed appeared to be the result of the different experimental conditions.

Table 4. Means of the thermal sensation votes for males at the A, B, C, D and E voting times for all tests at the three activity levels.

4(a). Low Activity Level

Relative Humidity (%)	Dry Bulb Temperature (F)	Mean Thermal Sensation Vote				
		A	B	C	D	E
25	66	4.0	3.8	3.8	3.8	4.0
	72	4.6	4.2	3.8	4.0	4.0
	78	5.0	4.8	4.8	5.0	4.4
45	66	3.0	3.2	3.4	3.4	3.4
	72	3.6	4.4	4.2	5.0	4.0
	78	5.0	4.8	4.8	4.6	5.2
65	66	3.6	3.6	3.4	3.8	3.8
	72	4.0	4.0	3.8	4.2	4.2
	78	5.4	5.8	5.6	5.2	5.2

4(b). Medium Activity Level

Relative Humidity (%)	Dry Bulb Temperature (F)	Mean Thermal Sensation Vote				
		A	B	C	D	E
25	60	3.2	4.0	4.0	3.4	3.4
	66	3.8	4.0	3.8	4.0	4.0
	72	4.4	4.2	4.4	4.6	4.4
	78*	5.0 4.2	5.2 5.4	4.8 5.6	4.2 5.4	4.8 5.2
45	60	2.6	3.0	3.4	3.2	3.6
	66	3.4	4.2	4.2	4.0	4.4

Table 4. (cont.)

4(b). Medium Activity Level (cont.)

Relative Humidity (%)	Dry Bulb Temperature (F)	Mean Thermal Sensation Vote				
		A	B	C	D	E
45	72	4.0	4.4	4.2	4.0	4.2
	78*	5.6 5.0	4.8 5.0	4.6 5.2	4.4 4.8	4.0 5.0
65	60	3.6	3.4	3.2	3.2	4.6
	66*	4.2 4.4	4.0 4.6	4.2 4.2	4.2 3.8	4.2 3.8
	72	4.8	5.0	4.6	4.6	4.6
	78*	5.4 4.6	5.0 4.8	5.2 4.0	4.6 5.2	5.0 4.4

*Two tests were conducted.

4(c). High Activity Level*

Relative Humidity (%)	Dry Bulb Temperature (F)	Mean Thermal Sensation Vote				
		A	B	C	D	E
25	54	2.6 3.0	2.4 3.4	3.2 3.6	2.8 3.4	2.6 3.6
	60	2.8 3.4	3.0 3.6	3.0 3.6	3.0 3.4	3.8 3.8
	66	4.2 3.2	4.6 3.4	4.6 4.0	5.4 3.8	4.6 3.8
45	54	2.0 3.2	2.6 3.6	2.8 3.8	2.6 3.8	2.6 3.8
	60	2.8 2.8	3.0 3.0	3.6 3.8	4.0 3.8	3.8 3.6
	66	5.2 3.8	5.0 3.6	4.6 4.4	4.6 4.6	4.8 4.0

Table 4. (concl.)

4(c). High Activity Level*

Relative Humidity (%)	Dry Bulb Temperature (F)	Mean Thermal Sensation Vote				
		A	B	C	D	E
65	54	2.8 3.4	3.0 3.4	3.0 3.4	3.0 3.2	3.2 3.4
	60	5.2 3.8	5.0 3.6	4.6 4.4	4.6 4.6	3.8 4.0
	66	5.6 4.2	4.6 4.6	5.2 3.2	5.4 2.6	5.6 4.2

*Two tests were conducted for each thermal condition.

Table 5. Means of the thermal sensation votes for females at the A, B, C, D and E voting times for all tests at the three activity levels.

5(a). Low Activity Level

Relative Humidity (%)	Dry Bulb Temperature (F)	Mean Thermal Sensation Vote				
		A	B	C	D	E
25	66	3.0	3.2	3.4	3.4	3.4
	72	4.4	4.0	4.2	3.8	3.8
	78	5.2	4.6	5.0	4.2	4.2
45	66	3.0	3.8	3.0	3.0	3.6
	72	4.4	4.4	4.0	4.0	4.0
	78	4.8	4.6	5.0	4.2	4.2
65	66	3.4	3.6	3.8	4.0	4.0
	72	4.8	4.6	5.0	4.2	4.2
	78	6.0	5.4	6.2	5.6	6.0

Table 5. (cont.)

5(b). Medium Activity Level

Relative Humidity (%)	Dry Bulb Temperature (F)	Mean Thermal Sensation Vote				
		A	B	C	D	E
25	60	3.4	3.2	3.4	3.0	3.2
	66	4.0	3.8	4.6	4.0	4.0
	72	4.8	5.0	5.0	4.4	4.6
	78*	5.8 5.6	5.6 5.6	5.8 5.4	5.6 6.4	5.4 6.4
45	60	4.0	3.6	3.4	3.6	3.0
	66	3.8	3.8	4.0	3.8	4.0
	72	4.8	4.6	5.2	4.8	4.8
	78*	6.6 5.4	6.2 5.2	6.6 5.2	6.4 5.0	6.0 5.0
65	60	3.8	3.6	3.0	2.8	4.0
	66*	4.0 4.2	4.4 4.0	4.2 4.0	4.6 4.2	4.8 4.2
	72	5.0	4.0	4.4	4.8	4.4
	78*	6.0 5.6	5.8 6.0	5.4 4.8	4.8 5.6	4.6 4.8

*Two tests were conducted.

Table 5. (concl.)

5(c). High Activity Level*

Relative Humidity (%)	Dry Bulb Temperature (F)	Mean Thermal Sensation Vote				
		A	B	C	D	E
25	54	4.0 2.4	3.8 2.6	3.4 2.6	3.4 1.8	3.2 2.2
	60	4.2 3.4	4.0 4.0	4.0 3.6	3.8 3.2	3.8 2.8
	66	3.8 3.6	3.6 4.4	4.0 5.6	4.4 6.4	4.0 4.4
45	54	2.6 2.2	2.8 2.4	3.2 2.2	2.6 2.0	2.4 2.0
	60	3.8 3.6	3.8 4.0	4.0 4.4	3.8 4.6	3.8 5.0
	66	5.2 4.8	5.2 4.6	5.6 4.4	4.6 5.6	5.2 5.6
65	54	3.6 3.8	3.2 3.8	3.0 3.0	3.0 3.6	3.4 4.0
	60	4.4 5.6	5.0 3.8	5.2 5.0	5.2 4.8	5.4 4.2
	66	6.2 6.0	5.8 6.6	6.4 6.0	6.2 6.8	6.4 6.8

*Two tests were conducted for each thermal condition.

of the high activity level was made and the temperature-humidity interaction was found nonsignificant for each of the five voting times for both sexes.

The method of least squares was used to fit a surface through the means of the "E" thermal sensation votes in the temperature-humidity plane. The final "E" votes were taken after

3 hours exposure to the thermal conditions. This length of exposure time allowed the subjects to become fully adjusted to the thermal conditions and thus it was concluded by Nevins et al., (61) that the final thermal sensation vote would indicate the subjects true thermal sensation. The following reeults for each activity were obtained from a multiple regression analysis of the means of the final thermal seneation votee.

A. Low Activity Level

1. The equations for the estimated mean thermal sensation vote as a function of temperatures and humidity were:

$$Ym = -2.755 + \underset{(0.0227)}{0.09722}\,T \qquad (1)$$

$$R^2 = 0.734 \quad Syx = 0.334$$

$$Yf = 113.769 - \underset{(0.804)}{3.219}T + \underset{(0.0056)}{0.0235}\,T^2 \qquad (2)$$

$$R^2 = 0.949 \quad Syx = 0.235$$

where,

Ym = Estimated population mean vote for college-age males.

Yf = Estimated population mean vote for college-age females.

T = DBT, F

( ) = Standard deviation of regression coefficient.

R^2 = Square of the multiple correlation coefficient (percent of variance accounted for by the joint action of the

independent variables).*

Syx = Standard error of estimate (a measure of the variation from the estimated mean vote).

2. There was a strong linear effect of temperature for the males. Quadratic effects of temperature and the linear effect of relative humidity were not significant at the 5% probability level. While relative humidity effects might be detectable over a wider range of humidities, the assumption of linearity with respect to temperature only will give an excellent approximation for the males.

3. A significant curvilinear effect of temperature was detected for females at the 5% probability level. The effect of relative humidity was not significant.

B. Medium Activity Level

1. The equations for the estimated mean thermal sensation vote as a function of temperature and humidity were:

$$Ym = -0.602 + \underset{(0.01235)}{0.06895}\ T \qquad (3)$$

---

*Maximum R^2 = 1.00. For R^2 = 0.80, eighty percent of whatever makes one subject vote differently than another is explained by the combination of independent variables given in the estimated mean vote equations. The remaining twenty percent of the variance in mean votes must be attributed to factors not measured in the test.

$$R^2 = 0.706 \quad Syx = 0.334$$

$$Yf = -4.292 + \underset{(0.0181)}{0.1242}\,T \qquad (4)$$

$$R^2 = 0.783 \quad Syx - 0.491$$

2. A strong linear effect of temperature resulted for both males and females. Although the linear effect of relative humidity and the quadratic effects of temperature were not statistically significant at the 5% probability level, they did appear sporadically. Therefore, these effects cannot be completely discounted and further tests over a wider range might show significance.

C. High Activity Level

1. The equations for the estimated mean thermal sensation vote as a function of temperature and humidity were:

$$Ym = -1.211 + \underset{(0.01725)}{0.0833}\,T \qquad (5)$$

$$R^2 = 0.343 \quad Syx = 0.360$$

$$Yf = -10.360 + \underset{(0.029)}{0.2111}\,T + \underset{(0.0087)}{0.0408}\,H \qquad (6)$$

$$R^2 = 0.833 \quad Syx = 0.603$$

where H = Relative humidity in percent.

2. A linear effect of temperature was detected for the males at the 5% probability level. The linear effect of relative humidity and the quadratic effects of temperature were not significant at the 5% probability level.

3. There was a strong linear effect on temperature and a smaller linear effect of relative humidity for females. The assumption of linearity gave an excellent approximation.

The mean vote at the end of the third hour of testing for the male and female subjects at each activity level is shown in Tables 6, 7, and 8.

Table 6. The mean thermal sensation vote after 3-hour exposure to the low activity level for males and females.

Relative Humidity	Dry Bulb Temperature		
	66	72	78
Males			
25	4.0	4.0	4.4
45	3.4	4.0	5.2
65	3.8	4.2	5.2
Females			
25	3.4	3.8	5.2
45	3.6	4.0	5.8
65	4.0	4.2	6.0

Table 7. The mean thermal sensation vote after 3-hour exposure to the medium activity level for males and females.

Relative Humidity	Dry Bulb Temperature			
	60	60	72	78
Males				
25	3.4	4.0	4.4	5.0*
45	3.6	4.4	4.2	4.5*
65	3.2	4.0	4.6	4.7*
Females				
25	3.2	4.0	4.6	5.9*
45	3.0	4.0	4.8	5.5*
65	2.8	4.5	4.4	4.7*

*Two tests were run. This is the average of the results.

Thermal sensation lines are shown in Fig. 7 for males and Fig. 8 for females, for the three activities. Also plotted on Fig. 7 and 8 are the corresponding lines for sedentary activity as defined by Nevins et al., (61). Because relative humidity was not found to be a significant variable, the three mean votes at each dry bulb temperature were combined and their means were presented in Fig. 7 and 8.

Table 8. The mean thermal sensation vote after 3-hour exposure to the high activity level for males and females.*

Relative Humidity	Dry Bulb Temperature 54	60	66
Males			
25	3.1	3.2	4.2
45	3.2	3.8	4.2
65	3.3	4.4	4.9
Females			
25	2.7	3.3	4.2
45	2.2	4.4	5.4
65	3.7	4.8	6.6

*Two tests were run for each temperature-humidity combination. The average of the results is presented.

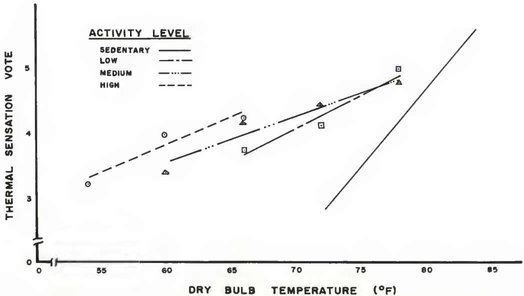

Fig. 7. Thermal sensation vote vs dry bulb temperature for males at four levels of activity after three hours exposure.

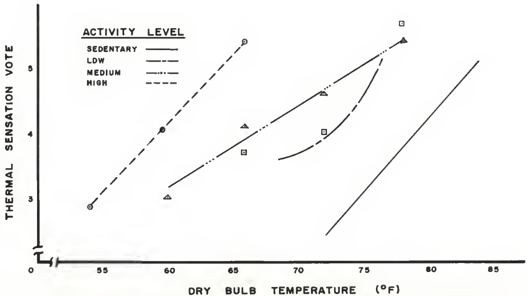

Fig. 8. Thermal sensation vote vs dry bulb temperature for females at four levels of activity after three hours exposure.

DISCUSSION

This atudy was a continuation of the ASHRAE comfort studies being conducted by the Institute for Environmental Research at Kansas State University. As stated in previous papers by Nevins et al., (61) and Rohles (65), thermal comfort is an extremely nebulous variable. There is a multitude of variables which may influence the reactions of the subjects. This study attempted to control as many of these variables as possible and thereby increase the over-all validity of the findings.

Four hundred twenty untrained observers served as subjects. Untrained observers were preferred over trained observers for the reasons stated by Nevins, et al., (61). First, they comprise a larger sample, making possible a more valid generalization; second, untrained subjects are more representative of the general population than trained professional observers; and, for this experimental design, the order of presentation of the test conditions is not important for statistical validity. Leopold (49) observed that large numbers of observations lack the accuracy of well conducted laboratory experiments but they have the great virtue of numbers and the absence of conscious psychological factors or systematic errors due to the employment of a few "trained subjects." Chrenko (11) recommended that although "it is often convenient to carry out experiments with a small group of subjects who are tested on numerous occasions . . . . the research worker should, when possible, investigate the reactions of the ordinary man and woman."

The criteria established by Nevins et al., (61) for control of the human factors (as defined by Rohles (65)), which must be considered when conducting environmental research on human subjects, were used for this study. This also provided a valid means for comparing the results between activity levels. Rohles' (65) reciprocative factors -- activity, clothing, exposure time and number of subjects by sex -- were identical for each thermal condition within an activity level. The organismic factors of basal metabolic rate and diet were not considered; however, biological rhythmicity was accounted for by conducting half of the tests in the afternoon and half in the evening. In addition, the variance in age was small. The physical factors, temperature and humidity, were used as the independent variables for the study.

Dry bulb temperature was used in this study as a factor for thermal comfort zone analysis because work by Chrenko (11), Glickman (22) and others have found that thermal sensations could be predicted more reliably from a knowledge of dry bulb temperature and effective temperature than from the mean skin temperature. Also, since the study was patterned after the Nevins et al., (61) sedentary study, it was desired to keep as much consistancy as possible.

Enlargement of the experimental design and reruns at given temperatures, as indicated in Tables 7 and 8, were necessary in the medium and high activity levels so that observed variability could be more fully explained. This included adding the 78F

test to the medium activity level design. In some cases, information received initially was not sufficient for proper statistical analysis; therefore, reruns were required to verify initial findings. However, a duplication of all test conditions was not felt justifiable. It was unfortunate that the low activity level tests could not be rerun due to lack of money and time because it was believed that the observed curvilinear effect seen in Fig. 8 was due to small sample size and not a true effect.

Pulse rate and evaporative heat loss data were analyzed to provide physiological information of the subject's reaction to the temperature and humidity conditions at each activity level. Sample data sheets that were used for pulse rate and evaporative weight loss analyses are shown in Fig. D-8 and D-9 of Appendix D. These analyses were not begun until the first series of tests (medium activity level) was nearly completed; therefore, a complete analysis of all conditions was not available. However, from the data obtained, trends were established and have been presented to help explain the variability seen in the thermal sensation vote lines of Fig. 7 and 8.

Figures 9, 10 and 11 give the pulse rate variations for both sexes during each activity cycle. The effect of relative humidity on pulse rate at the temperature investigated was not statistically significant. Therefore, the figures contain the variations with temperature only over the three-hour test period. Two recovery periods (stand portion of activity), representing a

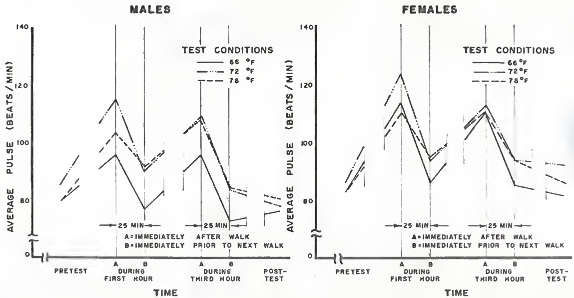

Fig. 9. Pulse rate variations for males and females during the low activity level tests.

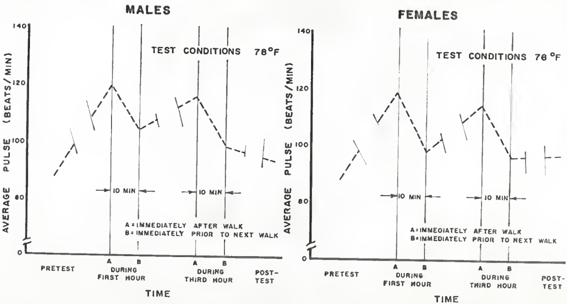

Fig. 10. Pulse rate variations for males and females during the medium activity level tests.

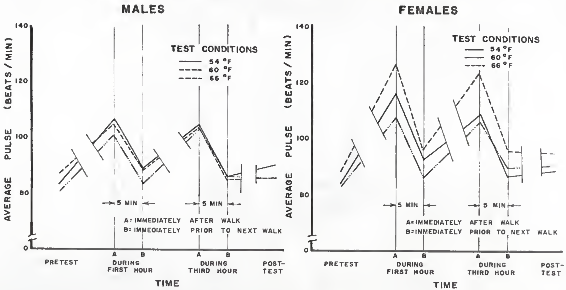

Fig. 11. Pulse rate variations for males and females during the high activity level tests.

sample of the first hour and third hour subjects' responses to the activity levels are shown. The nonsignificance of relative humidity was expected. Vernon and Warner (71), although their subjects were working in a somewhat higher dry bulb temperature range, found the effect of humidity on pulse rate to be almost the same at all the temperatures investigated. However, Glickman et al., (23), testing sedentary subjects, did find some significant differences in pulse rates due to relative humidity when dry bulb temperature was 78F and greater, and they attributed this difference as being caused by increasing body temperature, indicating that his subjects were no longer in the vasomotor zone.

The average pre-test pulse rate for male subjects was 83 beats per minute and 84 beats per minute for female subjects. For each test conducted, the final average pulse rates were slightly higher than the pre-test pulse rates for males and females with females showing a greater increase than males (but not significantly different at the 0.05 probability level).

Figure 9 shows the similarity of pulse rate variations for males and females participating in the low activity level tests. Significant deviation between the pulse rates at 66F and 72F was noted for males. No reason for this was observed, nor could an indication of the strong temperature effect for females as given in equation 2 be seen in Fig. 9. For men the combined average pulse rate immediately after walking during the first hour was 104 BPM (beats per minute) and 104 BPM during the third hour, while for females it was 112 BPM and 111 BPM. Immediately prior

to walking for males during the firet hour it was 86 BPM and 80 BPM during the third hour. For females it was 91 BPM and 90 BPM.

The decision to collect pulse rate data was made after 12 medium activity tests had been conducted; therefore, only the results of the final tests in the series were included in this study. Figure 10 shows males and females having similar pulse rate profiles for the highest dry bulb temperature investigated at the medium activity level. The uniformity of the average pulse rates from the first hour to the third indicates that at this activity level neither malee nor females were stressed significantly at the various temperatures investigated. The similarity of the thermal sensation lines in Fig. 7 and 8 for the medium activity level give strong support to the validity of this conclusion.

Comparison of the average pulse rates for males and females in Fig. 11 show that the three temperatures caused little variation in the pulee rate profile for males for the high activity level, while a significant effect of temperature was seen for females. This difference in male and female profiles corresponds with the eignificant difference between male and female thermal sensation votes at the high activity level as seen in Fig. 7 and 8. This variation in pulse rates and voting indicates that the high activity level wae causing a greater physiological stress in the female subjects than in the males. It was noted in Fig. 11 for females that both the high and low temperature pulse rates were greater than the pulse rate for the thermally neutral

temperature. The combined average pulse rate for men immediately after walking during the first hour was 104 BPM and 103 BPM during the third hour; for females it was 116 BPM and 112 BPM. Immediately prior to walking during the first hour the pulse rate was 87 BPM for males and 86 BPM during the third hour; for females it was 91 BPM and 90 BPM.

Although some deviations in pulse rate between temperature levels within an activity level were significant, the results were not consistent over the three activity levels. Therefore, the average decrease in pulse rate for all tests within the stand portion of a cycle is given in Table 9. No significant difference in pulse rate recovery was seen when comparisons were made between males, females and activity levels; however, a trend was observed indicating that males increased their recovery ability during the three hour tests while females' pulse rate recovery decreased. This would support the conclusion that the females were physiologically stressed somewhat more than the males, especially in the high activity tests. Carlson and Buettner (7) have defined physiological stress as the tendancy of the environment to cause a change in the individual. While Brouha et al., (6) have indicated that heart rate is the physiological variable that most faithfully represented the total strain induced by the simultaneous actions of work and heat, where strain is defined as the change in the homeotherm brought about by the stress. Brouha et al., (6) have shown that stress will cause a noticable increase in pulse rate over an hours time when performing on a treadmill

Table 9. The average decrease in pulse rate during the stand portion of activity tests just after a 5 minute walk period.

Average Decrease in Pulse Rate After Stand Time of:	Males		Females	
	During 1st Hour of Test	During 3rd Hour of Test	During 1st Hour of Test	During 3rd Hour of Test
	Beats per min.		Beats per min.	
5 minutes	17.2	18.1	25.0	22.2
10 minutes	15.5	17.3	20.7	18.1
25 minutes	18.4	21.6	24.3	20.3

or bicycle ergometer. This was not seen in Fig. 11, but the lessening of the female pulse recovery, another indication of stress shown by Brouha et al., (6), was observed in Table 9. Quantitatively, female pulse rate recovery appears to be greater than the male for the three activity levels. However, it should be noted that female pulse rates were approximately 10% higher than males immediately after walking. Thus, a larger range was available for recovery by females.

Heat loss by evaporation normalized for a unit body area was less for females than males although both were participating in the same test, wore similar Kansas State University clothing and worked at the same task.

Figure 12 presents the evaporative heat loss per unit of body surface area for the three activities and their respective dry bulb temperatures. Data from activity studies on clothed subjects by Houghton et al.,(34), Humphreys et al.,(38) and

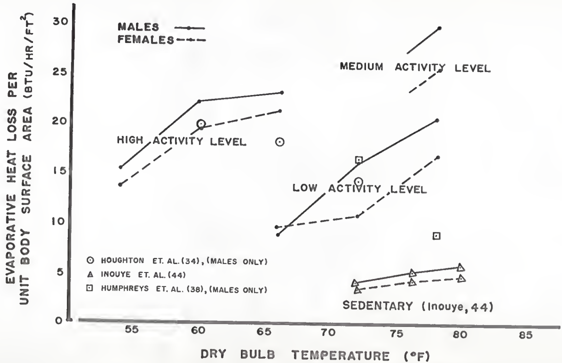

Fig. 12. Evaporative heat loss per unit body surface area vs test conditions (dry bulb temperature) for four activity levels for both males and females.

Inouye et al., (44) were included for the purpose of comparison at the thermally neutral temperatures. The 10 to 25 percent difference in male and female evaporation rates shown in Fig. 12 was consistent throughout the tests. For the reasons stated previously, only one set of data was collected for the medium activity level; therefore, it was not possible to make an overall analysis of evaporative heat loss. However, the trends observed have been indicated. From Fig. 12 it was observed that heat loss by evaporation increased for males and females as the dry bulb temperature increased for a given activity level. This observation agreed with previous results published by Humphreys et al., (38) and the data shown in Fig. 12 for Inouye et al., (44) with clothed sedentary subjects. The sedentary data was presented as an indication of the effect of activity on evaporation rate. With increasing activity, it can be seen that evaporation became a significant factor for body heat loss. Data on Fig. 12 by Houghton et al., (34), of evaporative heat loss for males at the three thermally neutral temperatures was quite similsr to the values obtained in this study. The data from Humphreys et al., (38) was obtained from theoretical calculations and showed close agreement with the observed low activity level value for males. Unfortunately, Humphreys (38) only presented values for the sedentary and low activity levels; therefore, it was not possible to compare his results with the medium or high activity levels.

The accuracy of the three activity levels in approximating

the desired 600, 800 and 1,000 Btuh activity levels at the designed neutral vote condition for males was investigated by using the evaporative heat loss and applicable heat transfer equations from Humphreys et al., (38), McNall and Sutton (55) and Jacob and Hawkins (45). The total metabolic rate was evaluated as the sum of the sensible and latent heat losses. The metabolic rate analysis is continued in Appendix E. Table 10 contains the results for the average male and female subject participating in the study.

Robinson (63) compared the effect of body size upon energy exchange in work for a large man (218 lbs, 72.5 in.) and a small man (134 lbs, 66.8 in.) and found that when both men worked at the same rate that heat production was proportional to body weight and that for these men, the large man produced in relation to surface area about 20 percent more heat than the smaller man. Thus, in this study the 20-30% difference in total metabolic heat loss (representing approximately 190.0 Btuh) between males and females shown in Table 10 may be attributed in part to the difference in average body sizes and external work required to perform the activity cycles. From DuBois (13) it was found that the average basal metabolism for 20 year old females was 8-10% less than for males of similar age. Similar observations of the physiological differences in males and females were made by Hardy and DuBois (24) and Hardy and Milhorat (25). Combining these previous findings with the observed physical differences in males and females (14% for body surface area and 20% for body weight),

Table 10. Metabolic heat loss for the average male and female subject near the thermally neutral condition for three activity levels.

Metabolic Heat Loss B/hr	25 Minute Stand 5 Minute Walk Cycle Dry Bulb Temperature 72F		10 Minute Stand 5 Minute Walk Cycle Dry Bulb Temperature 66F		5 Minute Stand 5 Minute Walk Cycle Dry Bulb Temperature 60F	
	Male	Female	Male	Female	Male	Female
Evaporation (measured)	335	195	382	267	471	350
Radiation & Convection (calculated)	357	307	430	370	495	426
Total Btuh	692	502	812	637	966	776

a difference in total metabolic rates of the amount observed could be expected. In some of the tests, however, a tendency for the female pulse to climb between the first and third hours was observed (Fig. 11); therefore it may be possible that females were storing some heat while the males were able to maintain homeostasis for each activity. The lower metabolic rate and the possibility of heat storage may explain why females were more sensitive to thermal conditions for each activity than the males as seen in Fig. 7 and 8. Body heat storage caused by the body generating more heat than is dissipated per unit of time will influence a person's sensitivity to thermal changes. A lower metabolic heat production rate allows thermal changes to have a greater effect on the subject because less heat is available

to meet the demand imposed by the environment.

The means of the five male and five female thermal sensation votes cast during the five voting periods of each test are shown in Tables 4 and 5 for males and females, respectively. An F test at the 0.05 probability level was made on the five voting times in each activity level. These indicated a significant temperature effect was present during each of the five votes for each activity level. The F values are shown in Tables D-6 and D-7 in the appendix for males and females, respectively. Relative humidity was sporadically significant except for the low and high activity levels for females. However, temperature was such an overwhelming factor for all five voting times, as shown by the quadratic effect in Equation 2 and in Fig. D-7 of the appendix, for the low activity level that the effect of relative humidity was considered of negligible importance for this activity level. Nevins et al., (61) reported that their study had revealed no significant differences between the second and third hour mean votes for sedentary male and female subjects. Similar observations and results were obtained in this study. The factors significant at the "C" vote (second hour) were significant at the "E" vote (third hour) and those factors insignificant remained insignificant for both sexes in each of the activity levels. The uniformity of the votes indicated that the subjects had achieved a thermal equilibrium with the environment during the last hour.

Figures 7 and 8 are presented for comparison of the three

activity level thermally neutral lines (vote of 4) and the dry bulb temperatures. Using data from "A Temperature-Humidity Chart for Thermal Comfort of Seated Persons" by Nevins et al., (61), a thermal comfort line for sedentary males and females was added to each of the figuree. It was noted that the low and medium activity sensation lines intersected near 78F in both figures. No explanation can be given for this except that the higher evaporation rate might possibly be causing the more active subjects to feel cooler because of their lower skin temperature.

Figure 7 indicated that men became less sensitive to dry bulb temperature changes as the activity level was increased. After nine teste were completed, at the high activity level, no temperature or humidity combinations were found statistically significant for males at the 5% probability level and 20% of the males variability could be explained. Therefore, a second series of nine tests at the high activity level were conducted. The results of the two series of tests were combined and the effect of dry bulb temperature was found to be significant at the 5% probability level. However, only 34% of the data variability was explained by the least squares solution (Eq. 5). Analysis of the final mean thermal sensation votes (Table 8) gave evidence that a temperature humidity interaction, although not statistically eignificant at the 5% level, was present. Because of the wide distribution of mean votes, as seen in Table 8, more observations at each of the nine test conditions will be required to better explain the remaining data variability. Presently, the

assumption of linearity with temperature gives the best description of male thermal sensation voting at the high activity level.

For the three activity levels, a range of 25 to 65% relative humidity caused no significant effect upon male comfort, although previous work with sedentary males by Nevins et al., (61) did indicate a small temperature-humidity interaction. Thus, the effect of relative humidity on human comfort appears to have less importance, both at temperatures below the sedentary thermal neutrality condition and within the thermally neutral zone for activity levels higher than sedentary. Rowley et al., (66) also found no significant effect of relative humidity on the feeling of comfort in his study of 275 office workers composed of both males and females.

The results for the female subjects were not as conclusive as those indicated for males; however, a strong temperature effect was observed for each activity level. At the low activity level, a strong quadratic effect of temperature was indicated. The reason for quadratic temperature effect cannot be explained but it was felt that future research with a larger temperature difference and a greater number of observations may indicate only a linear effect for temperature and a possible linear effect of relative humidity.

The high activity level produced some unexpected and unexplainable results for females. Equation 6 and Fig. 8 and 14 indicate a strong linear effect of temperature and relative humidity. A decrease in temperature and relative humidity sensitivity

similar to that observed for males was expected; however, the data showed that females were extremely sensitive to temperature and relative humidity changes. Referring to Fig. 11, the noticeable deviation between female and male pulse rates and differences in average body weight and body surface area offer plausible physiological reasons for the increased female sensitivity. Fatigue, causing physiological stress, may have also influenced the responses of the female subjects participating in the high activity level.

Although the relative humidities investigated for this study were found to have only a small effect on the subject's thermal sensation voting, it was noted that for each activity level, when the temperatures investigated within a thermally neutral zone were higher than the thermally neutral temperature for that activity, both male and female mean votes at those temperatures were influenced by the relative humidity. The 65% relative humidity would have the highest mean vote while the mean vote for 25% relative humidity would be the lowest. This observation was not seen at temperatures near or below the thermally neutral temperature. Therefore, it is probable that future comfort studies at temperatures above the thermally neutral zone for an activity level will find that relative humidity is a significant parameter, whose effect on a subject's thermal sensation is similar to that found for sedentary subjects at temperatures above the sedentary thermally neutral zone.

The thermally neutral zone for each activity level by

definition include those temperatures within one-half vote of the thermally neutral temperature lines shown in Fig. 7 for males and 8 for females. Shown in Table 11 are the thermally neutral zones for males and females at the three activity levels and for relative humidities between 25 and 65%. For each activity level the male thermally neutral zone overlapped the female zone and was from 3 to 8F degrees wider while comfort zones for sedentary males and females have shown female comfort zones to be wider than males (Hardy and DuBois, (24)). Also the sedentary male comfort zone is smaller than those found in this study. Perhaps the following observation made by Leopold (50) best explains why the male comfort zones became wider as the male worked harder. "In general," he stated, "it is observed that the more a person is confined in one position and one type of clothing, and the less occasion he has to move about, the more aware he will be of thermal environment."

Table 11. The thermally neutral zones* for males and females for three activity levels with relative humidity between 25 and 65%.

Activity Level	Males °F	Females °F
Low	64 - 75	67 - 75
Medium	60 - 73	63 - 71
High	56 - 68	57 - 62

*The thermally neutral zone includes those temperatures within one-half vote of the thermally neutral temperature lines.

The results of this study are presented in Fig. 13 and 14 for college-age males and females wearing standard clothing and exposed for three hours to the three activity levels. The lines shown for the four activity levels are suggested as the design criteria for human thermal neutrality. The figures include the thermally neutral temperatures presented by Nevins et al., (61) from the sedentary study. The strong humidity effect found for females in the high activity level is shown in Fig. 14. The lines were obtained by solving Equations 1, 2, 3, 4, 5 and 6 with Y equal 4 (the thermal neutrality scale's neutral vote) for dry bulb temperatures at relative humidities of 25, 45 and 65% Comparison of the lines for males and females from Fig. 13 and 14 and consideration of the thermally neutral zones in Table 11 were used to determine the following suggested thermally neutral temperatures for both males and females at the three activity levels: low activity level, 72F; medium activity level, 66F; and high activity level, 60F.

These results apply to individuals under essentially still-air conditions in a uniform environment with the mean radiant temperature maintained close to the dry bulb temperature. Further, the results are limited to individuals who have come to equilibrium with the environment after stabilization periods of approximately three hours. Thus, this study covers the responses of subjects to temperature and humidity with the other variables of the environment being so adjusted as to have a minimum effect on subjective reactions.

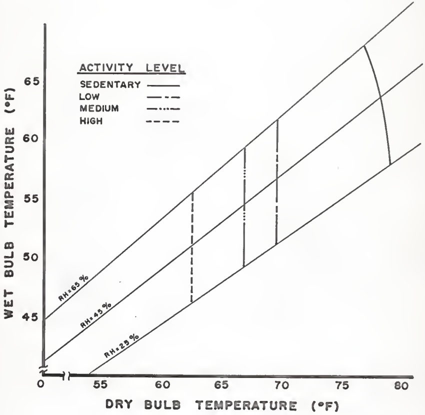

Fig. 13. Lines of thermal neutrality for four levels of activity for males.

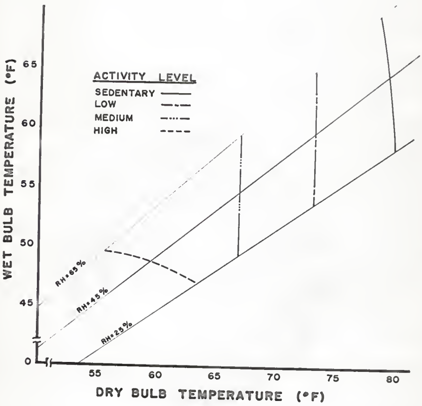

Fig. 14. Lines of thermal neutrality for four levels of activity for females.

SUMMARY

Four hundred twenty subjects, 210 male and 210 female, clothed, healthy and of college age, were used to investigate the thermal comfort (thermally neutral) zones for three levels of activity. The three activity levels (low, medium and high) resulting in metabolic rates of approximately 600, 800 and 1,000 Btuh for the average male subject, were obtained by using a step test. For each test 10 subjects, 5 male and 5 female, were exposed for 3 hours with minimum air velocity to one dry- and one wet-bulb temperature condition in the KSU-ASHRAE environmental test chamber. Thermal sensation votes were used to obtain the subjects evaluations of the environmental conditions. A statistical analysis of the means of the comfort votes for each test revealed that the dry bulb temperature was the primary factor that determined a subject's comfort sensation for each of the activity levels. Relative humidity between 25 and 65% was not a significant factor for male comfort sensations; however, the high activity female thermal sensation vote was influenced by relative humidity. In addition to the thermal sensation votes, observations were made of the pulse rate variations and evaporative weight loss experience by the subjects in the three activity levels. Male and female pulse rate profiles were quite similar in the low and medium activity levels. However, a difference was noted in the high activity level. The average evaporative weight losses for both males and females increased as the level of activity increased and for each activity level

the male evaporative loss was greater than the female loss both in total amount lost and when both were normalized per unit body area. The thermally neutral zones for each activity level shown in Table 11 indicated that in general as the level of activity was increased, male sensitivity to temperature changes decreased while female sensitivity increased. The thermally neutral lines for males and females at four levels of activity are shown in Fig. 13 and 14. The fourth activity level, sedentary, was obtained from the comfort study by Nevins et al., (61). The thermally neutral temperatures suggested for both males and females at the three levels of activity were low activity level, 72F; medium activity level, 66F; and high activity level, 60F.

CONCLUSIONS

The results of this study indicated that for metabolic rates of 600, 800 and 1,000 Btuh (approximately), the thermally neutral temperatures were 72, 66 and 60F, respectively. Clothed men and women preferred similar thermally neutral temperatures; however, the "Comfort Zone" for men at each metabolic rate included a wider range of temperatures than were included in the women's "Comfort Zone." Relative humidities of 25, 45 and 65% had little effect upon men and women's "Thermal Comfort" at the 600 and 800 Btuh (approximately) metabolic rates, but the relative humidity did affect the "Thermal Comfort" region for women at the 1,000 Btuh (approximately) metabolic rate.

Physiological data for men, as well as the resulting comfort zone trends, indicated that the men could perform at the three activity levels without fatigue for the three hour period, and probably could continue, even at the high activity level, for an entire eight hour work period. Similar data for the females lead to the same conclusion except at the high activity level where fatigue was indicated during the three hour period. Females would therefore not be expected to work continuously at the high level of activity throughout a normal work period of eight hours.

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A P P E N D I C E S

APPENDIX A

Justification for Substitution of "Neutral" for "Comfortable" in the Thermal Sensation-Vote Scale

Four sedentary conditions that were previously investigated by Nevins, et al., (61) and within the comfort zone were selected at random for the justification. They were: (1) 76 DB, 75 RH; (2) 78 DB, 25 RH; (3) 78 DB, 45 RH; and (4) 80 DB, 15 RH. The tests were repeated in the manner described by Nevins et al., with the only change being the substitution of "neutral" for "comfortable" in the thermal sensation vote scale. In recognition of the possibility of seasonal acclimatization affecting the thermal sensation voting, these tests were conducted in the winter season as was done in the Nevins et al. (61) study. A total of 80 subjects, 40 males and 40 females, were used. Table A-1 shows the aggregate observed thermal sensation votes of the subjects after 3 hours exposure to the environmental conditions.

The null hypothesis tested was that under identical thermal conditions there was no difference between the "effectiveness" of the two thermal sensation vote scales, thus that the proportion of cold, cool, slightly cool, neutral, slightly warm, warm, and hot votes on both scales would be the same. Statistical analysis through the use of chi-square techniques (Snedecor, 68) revealed that the substitution caused no significant change in the subject's thermal sensation vote at the 5% probability level. The chi-square value found was 4.04 while under the null hypothesis it would take a chi-square ($x^2_{.05,\ 2}$) of 5.99 to have significance.

Table A-1. Sedentary subjects' thermal sensation votes after a 3-hour exposure to four different environmental conditions in the comfort zone.

Title of #4 Vote	Vote		
	Slightly Cool 3	4	Slightly Warm 5
"Comfortable"	8	28	4
"Neutral"	6	23	11

APPENDIX B

Indoctrination Information Given Orally to the Test Subjects

The purpose of this test is to determine the effect that various temperature and humidity conditions have on exercising human beings. As soon as preparations are completed in the pre-test room, we will then take you into the test room next door. Stand at one of the tables until you are instructed to start walking up and down the steps provided. You will then walk for 5 minutes and return to your place at the table until instructions are again given.

At the end of the first hour, and each half hour thereafter, we will ask you to indicate your impression of the thermal sensation that you feel. We will provide a ballot that lists seven poseible thermal sensations (cold, cool, slightly cool, neutral, slightly warm, warm and hot). Circle the number that best describes your thermal eensation. The ballot will be picked up each time after you vote. Remember, vote the way you feel. Let no one else influence your vote!

While you are in the room you may play cards, study or engage in quiet conversation. You may smoke but we ask that you keep your smoking to a minimum.

When you are finished, we would like to have you go to your respective dressing rooms and get dressed. Girls put your shirts, trousers, and socks in one pile in your dressing room. Boys drop your uniforms and eocks down from upstaire on the table by the

pre-test room door. These will be picked up by the nurse and counted and placed in the laundry hamper. Do not leave uniforms in the upstairs restroom.

All persons participating in these tests will sign a receipt for your pay, $5.00, which will be given to you at the end of the test.

Are there any questions?

APPENDIX C

Analysis of Thermal Sensation Vote Variation with Time

In this study, the energy expenditure of the subject at the various activities was cyclic in nature. Therefore, the exact time during the cycle that a subject should vote had to be considered. In these experiments, under "comfortable" conditions while walking, more heat was produced than was required for homeostasus. When the subject stopped walking and stood quietly, he transferred the excess heat to the surrounding atmosphere. The gain and loss of metabolically generated heat produced a temperature gradient that the subject can detect and describe as feeling warmer or cooler. Pilot studies on metabolic production rates done in the Environmental Research Institute at Kansas State University (February 1966) revealed that when a subject was asked to express his thermal sensations on the thermal sensation scale, repeatedly after short intervals of time, the series of responses varied (as shown in Fig. C-1).

Three 3-hour tests were conducted with ten subjects, 5 males and 5 females, participating in each test. Room conditions and activity levels were as follows:

Test A - 60F, 45 RH and High Activity Level (Walk 5 min - Stand 5 min).

Test B - 66F, 45 RH and Medium Activity Level (Walk 5 min - Stand 10 min).

Test C - 72F, 45 RH and Low Activity Level (Walk 5 min - Stand 25 min).

The room conditions selected represented an expected thermal neutrality condition for each activity level, thus minimizing possible biasing from extreme room conditions. Each test was performed in the manner described in the text of this thesis.

Votes were taken during three stand portions of each test at approximately 0.15, 0.30 and 1.0 hour after the tests began. Normal voting procedure was used for the completion of the test. Five votes were taken during the five-minute stand period of Test A. The times were 0.0, 1.5, 2.5, 3.5 and 5.0 minutes after the subject stopped walking. Five votes were taken during the ten-minute stand period of Test B. Voting times were 0.0, 2.5, 5.0, 7.5 and 10.0 minutes after the subject stopped walking. Six votes were taken during the twenty-five minute stand period of Test C. Voting times were 0.0, 5.0, 10.0, 15.0, 20.0 and 25.0 minutes after the subjects stopped walking. The voting time profiles for the three activity levels at approximately one hour after the test began are shown in Fig. C-1. The voting time profiles at 0.15 and 0.30 hour were similar to those shown in Fig. C-1.

The mean vote of each cycle showed the effect of body cooling on the subject's thermal sensation vote. A time history analysis of the mean votes indicated that when the initial vote was taken, the subject's metabolic heat production was greater than that required for standing. Thus, heat was dissipated through vasodilation and skin evaporation. This excess energy caused the subject to describe himself as slightly warmer than

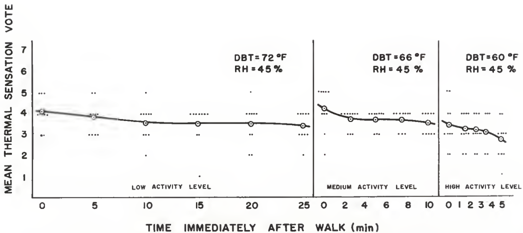

Fig. C-1. Mean thermal sensation vote vs time after completion of walk period for three levels of activity.

the mean. Continued standing enabled the body metabolic mechanisms to stabilize the heat loss per unit time and thus give a plateau effect (constant means) as seen in Fig. C-1. Finally, near the end of each stand period, lowered mean votes were seen indicating that body metabolism during standing was not sufficient to maintain homeostasus with the environmental conditions. Munro and Chrenko (57) in their investigation of thermal sensations and skin temperature of human feet have given a similar explanation of why a subject's thermal sensation will vary with time when resting after exercise.

The plot of mean votes was non-linear; however, the extremes did not deviate from the mean over 0.5 vote and deviations above and below the mean were approximately equal. Therefore, linearity was assumed and the time intervals selected to specify the exact times that a subject should vote after completing the walk period of each cycle in order to obtain the most valid vote for the period are listed in Table C-1.

Table C-1. The exact times that a subject should vote after completing the walk period for the three activity levels.

Activity Level	Time After Completion of the Walk Period Minutes
Low	12.0
Medium	4.0
High	2.0

APPENDIX D

Equipment: Anemotherm Air Meter - M. E. Dept. No. 1006
Operator: Dave Hemmel Date: January, 1966.
Dry Bulb Temperature: 71F
Measurements Taken: 3'9" above floor and no less than 4" from any wall.
Measurements in feet per minute. Upper figure refers to main fan and washer fan in operation. Lower figure refers to main fan only in operation.

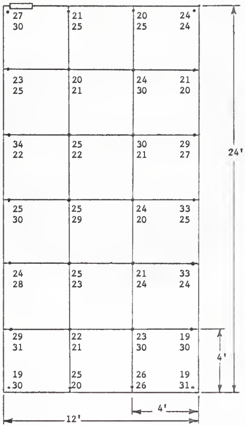

Fig. D-1. Test Room Air Velocity Profile.

ASHRAE DAILY RAW DATA SHEET

Activity:

A________ ________min.

B________ ________min.

DB____RH____WB____

Phase No.__Test No.__
Date:

Pretest: DB___RH___

Starting Time:

Time____

Conditions Outdoors:

DB____RH____

Name	Oral Temperature	Pulse	Time Subject Went to Bed (Military Time)	Hours of Sleep	Hours on Another Job During Past 21 Hours	Mental Exertion During Past 21 Hours	Physical Exertion During Past 21 Hours	Last Meal Time and Size (circle one) 1 2 3	Amount of Alcohol Drunk During Past 21 Hours	Health (Extent of Illness)	Health (Location of Illness)	Is Subject Menstruating?	Days Since End of Previous Menstruation	Degree of Concentration at Time of Vote A	Degree of Concentration at Time of Vote B	Degree of Concentration at Time of Vote C	Degree of Concentration at Time of Vote D	Degree of Concentration at Time of Vote E	VOTE A	VOTE B	VOTE C	VOTE D	VOTE E
1.																							
2.																							
3.																							
4.																							
5.																							
6.																							
7																							
8.																							
9.																							
10.																							
11.																							
12.																							

Meal Size:
0 = none
1 = light
2 = medium
3 = heavy

Last Normal Meal Time:
1 = Breakfast
2 = Lunch
3 = Dinner

Health (location):
0 = well
1 = head
2 = nose
3 = throat
4 = stomach
5 = 1 and 2
6 = 2 and 3
7 = 1 and 3
8 = all over
9 = other

Health (Extent):
0 = well
1 = slightly sick
2 = sick
3 = very sick

Mental Exertion:
1 = light
2 = medium
3 = heavy

Physical Exertion:
1 = light
2 = medium
3 = heavy

Degree of Concentration:
1 = light
2 = medium
3 = heavy

Alcohol Drunk:
0 = none
1 = minimum socially acceptable
2 = more

Menstruation:

Menstruation:
0 = no
1 = yes
2 = male

Fig. D-2. ASHRAE Daily Raw Data Sheet.

Weight Analysis Record Sheet

Project No. ______

Date: __________

DB ____ RH ____ WB ____

Activity:
Sedentary _____ min.
Stand ______ min.
Walk ______ min.

Subject's Name	Age	Oral Temperature	Height	Initial Weight (clothed)	Final Weight (clothed)	Weight Difference	Water (initial)	Water (final)	Water Difference	Total Weight Difference	Remarks
1.											
2.											
3.											
4.											
5.											
6.											
7.											
8.											
9.											
10.											

Fig. D-3. Weight analysis record sheet.

Pulse Rate Raw Data Sheet

Project No. 95

Date: ________
DB ___ RH ___ WB ___
Activity:
Sedentary _____ min.
Stand _____ min.
Walk _____ min.

		Time	Subject Lead No.	Subject Lead No.	Subject Lead No.	Subject Lead No.	Subject Lead No.	Subject Lead No.	Subject Lead No.	Subject Lead No.	Subject Lead No.	Subject Lead No.	Remark
Pretest													
First Hour	A												
	B												
	A												
	B												
	A												
	B												
	A												
	B												
	A												
	B												
Second Hour	A												
	B												
	A												
	B												
	A												
	B												
	A												
	B												
	A												
	B												
Third Hour	A												
	B												
	A												
	B												
	A												
	B												
	A												
	B												
	A												
	B												
Posttest													

A = After Walk
B = Before Walk

Fig. D-4. Pulse rate raw data sheet.

Table D-5. Analysis of variance table.

Sources of Variation	Degrees of Freedom	M.S.	F
Treatment Effects:			
Dry Bulb Temperature (DBT)	a-1	$(S.S.)_{DBT}/a-1$	$(M.S.)_{DBT}/(M.S.)_E$
Relative Humidity (RH)	b-1	$(S.S.)_{RH}/b-1$	$(M.S.)_{RH}/(M.S.)_E$
Interaction (DBT x RH)	(a-1)(b-1)	$(S.S.)_{DBT\ x\ RH}/(a-1)(b-1)$	$(M.S.)_{DBT\ x\ RH}/(M.S.)_E$
Error	ab(n-1)	$(S.S.)_E/ab(n-1)$	

Vote	A	B	C	D	E
		Low Activity Level			
Temperature	19.9*	6.75	12.66*	5.76	8.68*
Humidity	3.5	0.66	0.13	0.04	0.41
$F_{.05,2,4} = 6.94$					
		Medium Activity Level			
Temperature	15.33*	9.79*	9.90*	43.46*	15.70*
Humidity	3.16	0.69	0.5	2.47	0.16
$F_{.05,2,6} = 5.14$; $F_{.05,3,6} = 4.76$					
		High Activity Level			
Temperature	5.57*	6.25*	4.67*	2.34	5.10*
Humidity	5.69*	2.41	1.57	0.20	2.62
Temp. x Hum.	0.58	0.57	1.07	0.85	2.93
$F_{.05,2,9} = 4.26$; $F_{.05,4,9} = 3.67$					

*Significant at P = .05

Fig. D-6. F-values of the A, B, C, D and E mean thermally neutral votes for males at the three activity levels.

Vote	A	B	C	D	E
		Low Activity Level			
Temperature	348.8*	76.00*	45.5*	32.32*	230.*
Humidity	20.4*	7.00*	8.0*	2.49	18.3*
$F_{.05,2,4} = 6.94$					
		Medium Activity Level			
Temperature	75.26*	22.50*	48.10*	19.77*	21.0*
Humidity	1.05	0	5.51*	0.30	0.82
$F_{.05,2,6} = 5.14$; $F_{.05,3,6} = 4.76$					
		High Activity Level			
Temperature	17.88*	19.89*	26.31*	23.73*	29.46*
Humidity	11.97*	6.20*	4.26*	4.31*	12.53*
Temp. x Hum.	2.44	2.23	0.92	0.35	1.77
$F_{.05,2,9} = 4.26$; $F_{.05,4,9} = 3.67$					

*Significant at P = .05

Fig. D-7. F-values of the A, B, C, D and E mean thermally neutral votes for females at the three activity levels.

Analysis of Pulse Rates

Date:

Activity: Stand: min. Walk: min. Sit: min. Sex: Tempt: F RH: %
Date data 1-5 taken: Time:
Date data 6-10 taken: Time:
Date data 11-15 taken: Time:

No.	Pulse Rate (beats/min.)			During First Hour			During Third Hour		
	Before	After	Diff.	A	B	Diff.	A	B	Diff.
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
MEAN									
High ext.									
Low ext.									

Activity: Stand: min. Walk: min. Sit: min. Sex: Tampt: F RH: %
Date data 1-5 taken: Time:
Date data 6-10 taken: Time:
Date data 11-15 taken: Time:

No.	Pulse Rata (beats/min.)			During First Hour			During Third Hour		
	Before	After	Diff.	A	B	Diff.	A	B	Diff.
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
110									
12									
13									
14									
15									
MEAN									
High ext.									
Low ext.									

Fig. D-8. Analysis of pulse rates data sheet.

Analysis of Evaporative Heat Loss

Date:

Activity: Stand: min. Walk: min. Sit: min. Sex: Tempt: F RH: %
Date data 1-5 taken: Time:
Date data 6-10 taken: Time:
Date data 11-15 taken: Time:

Subject No.	Height in	Height cm.	Weight lbs.	Weight kg.	Body Surface Area ft^2	Body Surface Area m^2	Work Load ftlbs/hr	Evaporative Weight Loss lb/hr	Evaporative Weight Loss lt/hr	Evaporative Heat Loss Btu/hrft^2	Evaporative Heat Loss C/hr m^2
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											
MEAN											
Standard Error											
High ext.											
Low ext.											

Activity: Stand: min. Walk: min. Sit: min. Sex: Tempt: F RH: %
Date data 1-5 taken: Time:
Date data 6-10 taken: Time:
Date data 11-15 taken: Time:

Subject No.	Height in	Height cm.	Weight lbs.	Weight kg.	Body Surface Area ft^2	Body Surface Area m^2	Work Load ftlbs/hr	Evaporative Weight Loss lb/hr	Evaporative Weight Loss lt/hr	Evaporative Heat Loss Btu/hrft^2	Evaporative Heat Loss C/hr m^2
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											
MEAN											
Standard Error											
High ext.											
Low ext.											

Fig. D-9 Analysis of evaporative heat loss data sheet.

APPENDIX E

Analysis of Metabolic Heat Loss of Human Body

Within the thermally neutral zone it is essential that the human body lose thermal energy at the same rate as it is produced. The energy is produced by the process of metabolism and is dissipated to the surroundings by the heat transfer channels of radiation, convection, evaporation and conduction. Heat transfer by conduction plays a relatively small role between the body surface and the surroundings and is therefore usually integrated with the convection quantity in heat balance estimates.

The heat balance for the human body can be represented by the expression:

$$M = E \pm R \pm C \pm S \qquad (1)$$

where: M = rate of metabolic heat production within the body.
E = rate of evaporative heat loss.
R = rate of radiative heat loss or gain.
C = rate of convective heat loss or gain.
S = rate of heat storage within the body, resulting in a change in body temperature.

When the body is in a sedentsry condition and in the comfort zone, the storage term, S, is assumed equal to zero and the evaporative term, E, is assumed to be minimal (represented by insensible perspiration from the skin and lungs). Radiation and convection account for about seventy-five percent of the heat loss within the thermally neutral zones for sedentary persons. Within the thermally neutral zones for different levels of activity, storage is equal to zero while sensible and latent heat loss

increase to maintain the necessary heat balance.

The equation for sensible heat loss from the body (R+C) which was judged to be best suited to this specific problem was given by A. C. Burton and shown in Humphreys et al., (38). It is applicable to both nude and clothed subjects. The equation was written as:

$$R + C = \frac{A\ (t_s - t_a)}{K\ (I_a + I_c)} \qquad (2)$$

where: $R + C$ = sensible loss from the average man, Btuh.
A = body surface area, ft^2.
t_s = skin temperature, F.
t_a = air temperature, F.
I_c = insulation of clothing, in clo units.
I_a = insulation of air, in clo units.
K = conversion constant for clo., $\frac{\text{deg F}}{\text{BTU/hr,ft}^2}$

The clo, defined in terms of resistance rather than conductance units is:

$$0.88 \quad \frac{\text{deg F}}{\text{BTU/hr,ft}^2}$$

The ordinary business suit with the usual underclothing has an insulating value of approximately 1 clo.

Equation (2) has been used to calculate sensible heat losses, R + C, from the average male and female subjects at the thermally neutral temperature for the three activity levels. The latent losses, E, were calculated using the measured mean evaporative heat loss at each of the thermally neutral temperatures. The results are shown in Table E-1. The skin temperatures were

Table E-1. Sensible and latent heat losses for males and females at three activity levels.

Sex	Activity	Air Tempt. (°F)	Skin Tempt. (°F)	Sensible Heat BTU/hr	Latent Heat BTU/hr	Total Metabolic Heat BTU/hr
Males	Low	72	91.5	357	334	691
	Medium	66	89.5	430	382	812
	High	60	87.0	495	471	961
Females	Low	72	91.5	307	195	502
	Medium	66	89.5	370	266	636
	High	60	87.0	426	350	776

taken from a study presently in progress in the Institute for Environmental Research. The values were obtained from male subjects only and since information on skin temperature for females could not be found, female skin temperatures were assumed the same. The clo value of 0.52 given for the K.S.U. special clothing was used for I_c. The insulation value for air was taken from a chart given by Humphreys et al., (38) and found to be 0.76 clo for an air velocity of 40 FPM.

VITA

James R. Jaax

Candidate for the Degree of

Master of Science

Thesis: AN INVESTIGATION OF THERMAL COMFORT (THERMALLY NEUTRAL) CONDITIONS FOR THREE ACTIVITY LEVELS

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Professional Experience: Worked in the Institute for Environmental Research at Kansas State University from February, 1965 to January, 1967, conducting environmental studies on human comfort, a part of which are described in this thesis; during this period, was employed for three months by NASA, Manned Spacecraft Center, Houston, Texas as an Environmental Control Engineer; is a member of the Kansas Engineering Society, Sigma Tau and Pi Tau Sigma.

AN INVESTIGATION OF THERMAL COMFORT (THERMALLY NEUTRAL) CONDITIONS FOR THREE ACTIVITY LEVELS

by

JAMES RONALD JAAX

B. S., Kansas State University, 1965

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1967

Four hundred and twenty lightly clothed, healthy, college age subjects, 210 males and 210 females, were investigated to determine the thermal comfort (thermally neutral) conditions and zones for three activity levels. The three activity levels, low, medium and high, representing approximate metabolic rates of 600, 800 and 1,000 Btuh for the average male subject, were obtained through the use of a modified step test. Untrained subjects were exposed in groups of 10, 5 males and 5 females, for three hours to a predetermined thermal condition in the KSU-ASHRAE Environmental Test Chamber. The thermally neutral temperatures desired for each activity level as indicated by thermal sensation votes were 72F for the low activity level, 66F for the medium activity level and 60F for the high activity level. Males and females preferred similar thermally neutral temperatures; however, the "comfort zone" for males at each metabolic rate included a wider range of dry bulb temperatures than were included in the female's "comfort zone." Relative humidities of 25, 45 and 65 percent had little effect upon males and females' "thermal comfort" at the 600 and 800 Btuh metabolic rates, but the relative humidity did significantly effect the thermal comfort zone of females at the 1,000 Btuh metabolic rate. The thermal comfort (thermally neutral) zones for males and females at the three activity levels were: low activity, 64-75F for males and 67-75F for females; medium activity, 60-73F for males and 63-71F for females; high activity, 56-68F for males and 57-62F for females.

Observations made of the subjecta pulse rate and evaporative

heat loss indicated that subjects could be expected to perform at the activity levels investigated for an entire work day of eight hours. A probable exception was seen at the high activity level for females, where there was some evidence of fatigue.